MULTIBODY MODELING AND MULTI-OBJECTIVE OPTIMIZATION OF A SIX-WHEELED STEERABLE VEHICLE AND ITS MOTION CONTROLLERS

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ABSTRACT

This work describes multibody modelling and multi-objective optimization of a six-wheeled vehicle and its motion controllers. Compliant contact models are used in order to suitably represent the rolling/slipping regime at the wheel-terrain interaction. The multibody dynamic simulation model simulates multiple cases of the vehicle travelling on a soft terrain. The parameters of this model can be adjusted and its performance calculated through some criteria. Since there are several performance criteria, the problem was formulated as a multi-objective/multi-case optimization problem. Finally Monte Carlo simulation and Anti-optimization are used to assess robustness of the obtained results.

Keywords: multibody dynamics, multi-objective optimization, terramechanics, planetary rover, mobile robotics.

INTRODUCTION

Powerful rovers will be developed in the context of the European Space Agency's (ESA) Aurora programme, which aims for planetary exploration. The ExoMars rover, as described in [1], [2], [3] and [4], is a six-wheeled rover under development for Mars exploration inside this program. Such vehicles that drive up rocks, loose soil and general slippery and uneven terrain often need high mobility capabilities. Modelling and design of a high-performance autonomous vehicle is generally a difficult task. Engineering requirements are even more stringent since some characteristics are highly desired but also conflicting, as light weight and high traction for example.

We understand this problem as an optimization problem with multiple criteria. The structure of the vehicle must be optimized for all-terrain navigation and several phases of its life-cycle. Some approaches in the literature provided means to evaluate vehicles with distinct configurations. In [5] a terramechanics approach was taken into account together with a set of static models relating soil and mechanical configuration of a vehicle. Kinematic models and metrics were proposed by [6] aiming at mobility evaluation of distinct mechanical configuration of vehicles.

These works are based on static or kinematic models and are restricted to evaluation. We present an approach based on dynamic models capable of considering a broad range of performance criteria (static, kinematic and dynamic). This approach is not restrained to evaluation, but also employs parameter synthesis aiming at multi-objective optimization of some stated criteria. To achieve robustness, the vehicle is exposed to a worst case situation, where performance is decreased. This worst case scenario is found through Anti-optimization, [7].

For the current work two vehicles and two specific situations were defined. The first one is the six-wheeled vehicle with compliant contact model and simplified terramechanic models. The second is a four-wheeled vehicle with slippery behaviour on a rigid terrain. The former was taken as a first step to employ the general optimization procedure presented here; this model is simpler to simulate in the context of successive parameter variations. That's the reason because the four-wheeled vehicle is a first attempt in the optimization process of the six-wheeled vehicle. Optimization of the six-wheeled vehicle model is currently under development, but the performance criteria and motion controllers are the same for both vehicles. The next sections will give an overview of the multibody simulation model employed, the controllers' architecture for steering and driving the wheels, definition of performance criteria, procedure to synthesize the parameters and some intermediate results.

THE MULTIBODY SIMULATION MODEL OF THE SIX-WHEELED ROVER

The simulation model of the vehicle is based on the ExoMars rover (see figure 1) and developed with the MultiBody package in Dymola®. A three-bogie suspension system is employed with six rigid wheels in contact with soft surface without obstacles but considering uneven terrain (see figure 2).

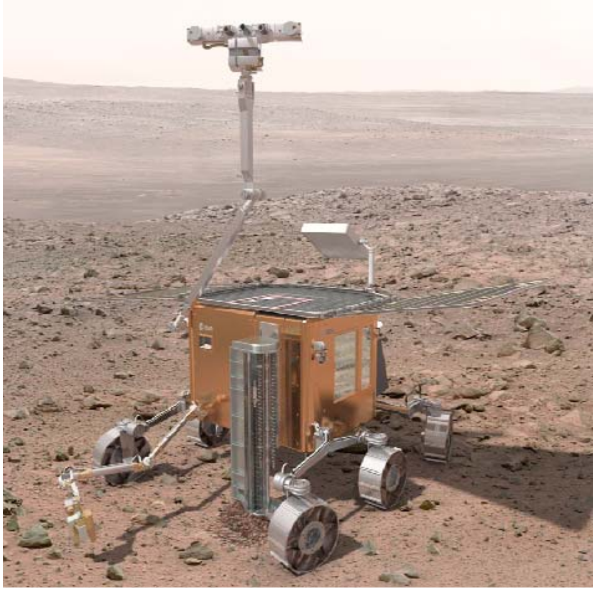

Fig. 1. Artist's view of the ExoMars rover [1] for future planetary mission to Mars scheduled for launch in January 2018; total mass including scientific instrumentation is 250kg; 6 wheels, each wheel actuated for driving and steering (courtesy: ESA).

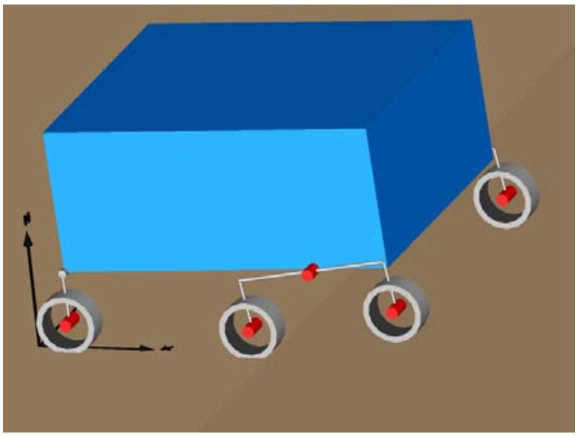

Fig. 2. Scenario of rover simulations in Dymola.

A three dimensional compliant model was developed in order to cope with the forces in the normal direction (to "support" the vehicle) and in the tangent plane that allow the rover to move. These compliant models are devoted to solve two specific problems: static indeterminacy in calculating forces/torques on the six wheels of a rover in contact with the terrain; and transition between rolling contact and slipping over the surface. It was implemented in Dymola® as a simple spring-damper analogous system:

$$F_\eta = k_\eta(\eta - d) + b_\eta \dot{\eta} \tag{1}$$

where F_η and η are the force and displacement in the corresponding direction (driving, sideways or perpendicular to the surface) in the body-fixed coordinate frame of each wheel. The parameters k_η, b_η and d are respectively stiffness, damping and the desired offset. This last parameter is defined as zero for the tangent plane forces and $d = r - z$ for the normal force. Where r is the radius of the wheel and z the corresponding sinkage.

The difference between thrust and motion resistance forces, i.e. the drawbar pull DP, for the considered rigid wheels can be described as follows:

$$DP = T_t + T_g - R_c - R_b - R_g \tag{2}$$

Thrust forces in the second term of (2) are respectively: tractive thrust T_t provided by the shear stress equation [9] and the contribution of the grousers T_g equally distributed over the surface of the wheel. Resistance forces are respectively: compaction R_c, bulldozing R_b and gravity's influence R_g. Note that each wheel has its corresponding normal force and sinkage as individual characteristics, it implies in different drawbar pull for each wheel. The following wheels (middle wheels and rear wheels) in this "triplet" configuration have an additional sinkage due to multipass effect, as a result of (1) this is properly distributed over the articulated structure of the rover with its three-bogie frame.

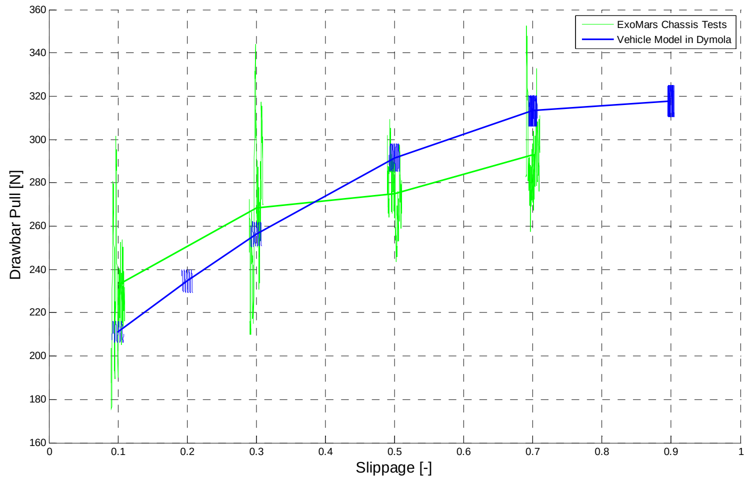

Fig. 3. Drawbar pull as a function of slippage for Mars soil simulant DLR-D2, experimental data taken from [1].

In figure 3, the drawbar pull of the vehicle simulated in Dymola® at the same conditions of the corresponding experiment with the ExoMars breadboard chassis tests are presented as a function of slippage for the same soil characteristics. Note that the force measurements were horizontally strongly compressed and placed close to the corresponding slippage value in the diagram. The simulation results can be improved with an additional tuning effort (not yet performed here) and implementation of soil randomness characteristics in the tractive thrust model.

CONTROLLERS' ARCHITECTURE

Figure 4a shows the steering controller, it is composed of a PD angular position controller cascaded with a PI current controller. The desired angular position is adapted to assume a ramp-like behavior, in order to obtain a smoother time response. Figure 4b shows the driving controller, it has a PI velocity controller also cascaded with a PI current controller. The reference is smoothed by a dynamically saturated feed forward filter with a slip ratio feedback path. It tends to decrease the rise time of the reference input as long as the slip increases.

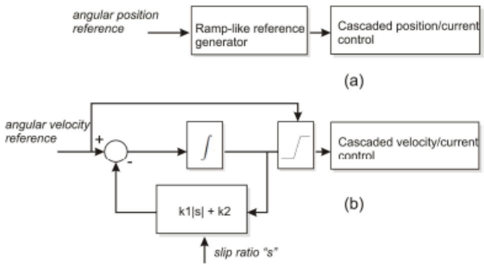

Fig. 4. Simple control systems for (a) steering and (b) driving of each wheel.

PERFORMANCE CRITERIA

Since the configuration of the vehicle and the architecture of the controllers were previously defined, their parameters have to be chosen in order to achieve some specification goals. Some metrics were established to account for performance of the vehicle in three distinct categories called: System, Control and Mobility metrics.

Some parameters of the mechanical structure combined with parameters of the steering and driving controllers can improve the performance of the vehicle in the view of those categories. Environmental parameters can give an idea of how well the vehicle behaves on a specific type of surface, e.g. a surface which supports high or low traction.

The idea is to use a set of parameters (those of the geometry of the mechanical structure and the controllers' parameters) to improve performance and another set (soil parameters) to robustness assessment. The behavior of the vehicle constrains dynamically the achievable performance. Table 1 shows the performance criteria properly organized in the three categories of metrics.

Table 1. Performance criteria

Category	Name	Description
System	STMa	Total mass of the system
	SPDr	Average power of the driving motors
	SPSt	Average power of the steering motors
Control	CADr	Control activity of the driving motors
	CASt	Control activity of the steering motors
	CEDr	Accumulated error of the velocity control
	CESt	Accumulated error of the position control
	CODr	Maximal overshoot of the velocity motors
	COSt	Maximal overshoot of the steering motors
Mobility	MSLo	Accumulated longitudinal slip
	MSLa	Accumulated lateral slip
	MTTd	Total travelled distance

PARAMETER SYNTHESIS / OPTIMIZATION RESULTS

The parameter synthesis was carried out by MOPS (Multi-Objective Parameter Synthesis) in the Matlab environment. MOPS was developed at DLR and its results tested in aircraft control systems as in [8]. As an example consider the parameter synthesis of the four-wheeled vehicle driving over slippery rigid terrain. The starting structure had a mass of 19.6 kg, and the new structure 4.36 kg. The other criteria were also compared with its respective values for the initial set of parameters, see figure 5 in scaled values for an overview of the general improvement.

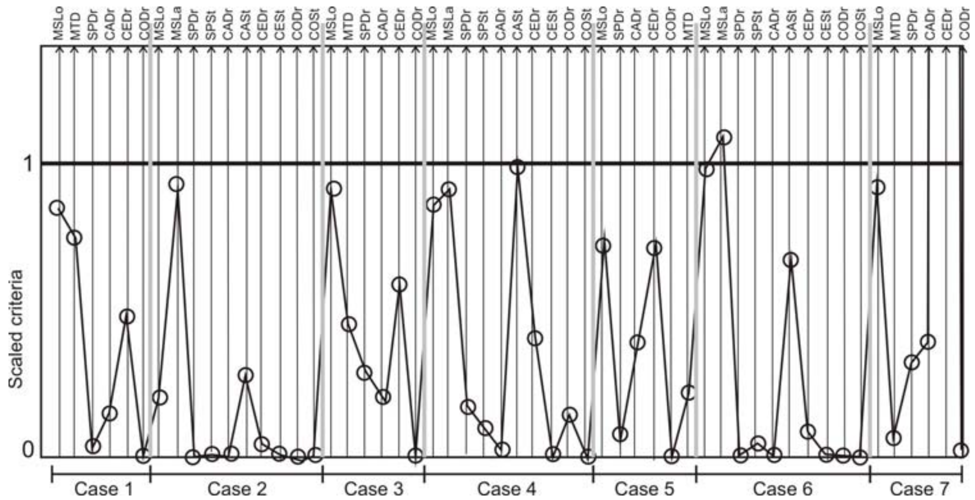

Fig. 5. Normalized criteria in parallel co-ordinates compared with metrics computed for initial solution. Solid horizontal line represent initial performance of the system. Cases: 1) Driving straight ahead over the plane; 2) with Ackermann steering over the plane; 3) straight ahead on a 20° incline; 4) equal steering on a 20° incline; 5) case 1 in low-traction terrain; 6) case 2 in low traction terrain; 7) case 3 in low-traction terrain.

CONCLUSIONS

Modelling and optimization of the entire structure of the six-wheeled rover are currently in development by the authors. Once a simulation model is obtained it is not guaranteed to achieve a good performance during the optimization procedure, because there are a lot of parameters which can lead to simulation instability. These parameters and initial conditions must be properly determined to build a simulation model capable of operating on a broad range determined by the changes settled by optimizer. On the other hand, simpler intermediate models (as single wheel models and four-wheeled vehicle model) are currently used as an attempt to find reasonable results which can be used as initial values for the optimization of the entire six-wheeled rover.

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